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Study on spectral shift of infrared multilayer thin film filters by using of equivalent index locus

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Abstract

Spectral shift of infrared multilayer thin film filters, which use lead telluride and zinc sulfide as thin film materials, when used under cryogenic circumstance, was investigated. As the index of lead telluride varies with the change of temperature, its influence on the performance of filter must be taken into consideration when there is a temperature difference between preparation and application circumstance. A shift model was established on the basis of interlayer compensating effect of multilayer thin films, value of wavelength shift was calculated using equal dividing method, and the calculated result is well coincident with the measured one.

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Keywords: optical thin film filters; lead telluride; spectral shift; cryogenic circumstance

1. Introduction

Bandpass optical thin film filters are of important use in space optical systems. A filter with pass-band of 10.4~12.5 m was designed and prepared at our laboratory, with lead telluride and zinc sulfide used as thin film materials. As the filter will be used under cryogenic circumstance of space, and the index of lead telluride varies with the change of temperature[1], its influence on the performance of filter must be taken into consideration. In this paper, study on the spectral shift of thin filter with temperature was made by use of equivalent index locus method.

2. Film structure of the filter

A bandpass optical thin film filter has been formed with a long-wavelength cutoff filter and a short-wavelength cutoff filter. Structures of both cutoff filters are the form of $(0.5LH0.5L)^m$. Where H means a layer of thin film of high index with optical thickness of one forth of center wavelength, $0.5L$ means a layer of thin film of low index with optical thickness of one eighth of center wavelength, and m is periodicity. Equivalent index of this kind of

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center-symmetrical thin film structure will not vary with change of m, so we can study only one single period. Germanium was used as substrate material, and lead telluride and zinc sulfide were used as high index and low index thin film materials, respectively. Cutoff wavelength of long-wavelength filter and short-wavelength filter are 10.4μm and 12.5μm, respectively.

3. Equivalent index locus technique

Draw up the equivalent indices of a multilayer thin film structure, which varies with growth of thin film, on a complex plane, and we can get the equivalent index locus. Locus of a single layer of dielectric thin film is a circle or an arc that centered on real axis. Assume there is a single layer of thin film with index of n on substrate of index $\alpha+i\beta$, then there is[2]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta & \frac{i}{n}\sin\delta \\ in\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} 1 \\ \alpha + i\beta \end{bmatrix} \quad (1)$$

Where $\delta = \frac{2\pi}{\lambda} nd$, which is the phase thickness of growing thin film and d is thickness of the film.

Equivalent index of the combination is $Y=C/B$, which is generally complex, if expressed in the form of $x+iy$, then it can be written as:

$$Y = x + iy = \frac{\alpha\cos\delta + i(n\sin\delta + \beta\cos\delta)}{(\cos\delta - \frac{\beta}{n}\sin\delta) + i\frac{\alpha\sin\delta}{n}} \quad (2)$$

Make real part and image part of both sides equal separately, and eliminate δ, then we can get equation of equivalent index:

$$x^2 + y^2 - \frac{\alpha^2 + \beta^2 + n^2}{\alpha} x = -n^2 \quad (3)$$

And this is equation of a circle that centered at $(\frac{\alpha^2 + \beta^2 + n^2}{2\alpha}, 0)$ and cross point $(\alpha+i\beta)$.

Equivalent index locus of a multilayer thin film structure was formed with a series of circles or arcs, one start at the end of another. Each circle or arc corresponding to a single layer of thin film, the intersection of locus and real axis is the extreme value point of reflectance of multilayer thin film structure. Fig. 1 shows equivalent index locus of a three-layer structure, s_i and e_i represent start point and end point of each layer, respectively, while i equals 1, 2, 3, which means the three layer of thin films.

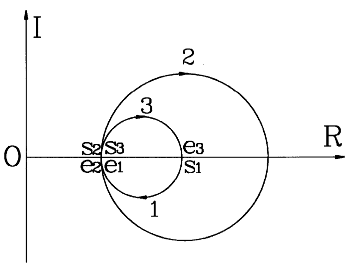

Fig. 1 Equivalent indices locus of a three-layer thin film structure.

4. Spectral shift model

When extreme value method was employed to control the deposition of multilayer thin films, if deposition of one layer of thin film was stopped before reflectance reach extreme value, another extreme value will appear in the deposition course of next layer, a little smaller then that of precise condition. If one layer of thin film was stopped after reflectance reach extreme value, the next extreme value will appear before the next layer reach desired thickness. This phenomenon was called compensating effect of multilayer thin film[3]. Fig. 2 shows the compensating effect of two layer of thin films represented with A and B. Phase thickness error δ_A was caused by the control error of layer A, then phase thickness error δ_{BA} was introduced into layer B, δ_A and δ_{BA} are opposite while their absolute value are equal. If δ_A is an over-thickness error, then it will be compensate by layer B with less-thickness error, phase thickness error δ_B of layer B will be compensated by the next layer.

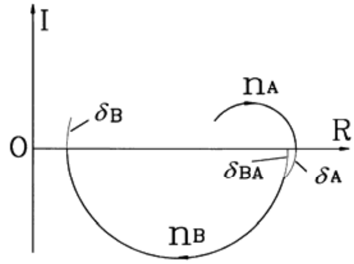

Fig. 2 Diagrammatic graph of compensating effect of multilayer thin films.

The performances of optical thin filters were determined by index and thickness of each layer of thin film. When filter designed and manufactured at room temperature was used under space cryogenic circumstance, thickness of each layer of thin film will not change, but index of lead telluride will become bigger. Then the performance of filters will affected by two factors, first, change of index of lead telluride layer bring about change of center wavelength of multilayer structure; second, cutoff wavelength of cutoff thin film filters λ_C was calculated by the following equation:

$$\frac{\lambda_0}{\lambda_C} = 1 \pm \frac{2}{\pi}\sin^{-1}\left(\frac{n_H - n_L}{n_H + n_L}\right) \tag{4}$$

Where λ_0 was center wavelength, optical thickness of layer H was one forth of it and that of layer L was one eighth of it.

So we can see from above that relative variation of high and low index will cause change of the ratio of λ_0 to λ_C, then cause the extension or narrowing of cutoff band, the final performance of thin film filter was composite result of the above two factors.

Now study a structure of a substrate and three layers of thin film. For the convenience of drawing of equivalent index locus, choose a reference wavelength as one half of center wavelength, then phase wavelength of the first and third layer will be $\pi/2$ and that of the second layer will be π according to the definition of phase thickness. Equivalent index locus of the three layers will be a semicircle, a circle and a semicircle, respectively (Shown in Fig. 1).

As index of lead telluride will increase with decreasing of temperature, phase thickness of the second layer will bigger than π under cryogenic circumstance, while those of the first and third layer can be seen as constant because of tiny variation of index of zinc sulfide. Then equivalent index locus of the second layer will be more than one circle, and the end of whole locus will pass over the real axis, Fig. 3 shows this case, the symbols is the same as those of Fig. 1.

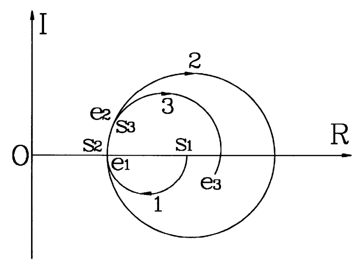

Fig. 3 Equivalent indices locus of three-layer thin film filter under cryogenic circumstance.

Use n and n' represent index of lead telluride at room temperature and that under cryogenic circumstance, respectively. Choose reference wavelength under cryogenic circumstance as $\lambda'=(n'/n)\times \lambda$, where λ means the above mentioned reference wavelength which is half of center wavelength. Then equivalent index locus of the second layer will be exactly one circle and those of the first and third layer will be less than one semicircle, and the end of the whole locus will not reach the real axis. So it can be thought that there is a value of wavelength between λ and λ', when use this wavelength as reference wavelength, the end of the whole locus will just on real axis due to the compensating effect of control errors. We think this wavelength is just half of center wavelength of the multilayer structure under cryogenics circumstance. Fig. 4 shows this case, the symbols are the same as those of Fig. 1.

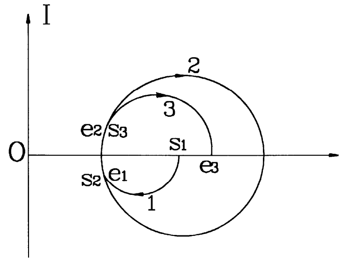

Fig. 4 Equivalent indices locus of three-layer thin film filter under cryogenic circumstance after changing reference wavelength.

Wavelength was calculated by use of equal dividing method. That is, take the mean of λ and λ' as reference wavelength, calculate the equivalent index of the structure of substrate and three layers of thin film, then adjust the reference wavelength according to the locus of calculated equivalent index to make the end of the locus just on real axis. In practice, when distance between the end and real axis is smaller than a provided value, calculation can be finished.

After center wavelength under cryogenic circumstance was calculated, cutoff wavelength of two cutoff thin film filters can be calculated by equation (4), then optical shift of the whole thin film filter. When index of lead telluride at room temperature and temperature of 105K was lead into, which is 5.64 and 5.91, respectively, calculated result shows that cutoff wavelength of long-wavelength filter changed from 10.4 μm to 10.85μm and that of short-wavelength filter from 12.5 μm to 12.62 μm at temperature of 105K. Fig. 5 shows the measured performance of the filter at 290K and 105K, which can be seen as coincide with the calculated value.

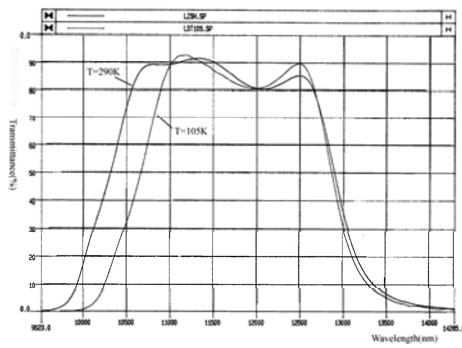

Fig. 5 Measured optical performance of the thin film filter at temperature 290K and 105K.

5. Conclusions

The coincidence of calculated and measured value of optical shift of thin film filter means that the established shift model can be thought as right. Namely, first, variations of index of film materials cause change of center wavelength of multilayer structure; Second, relative variation of high and low index will cause change of ratio of center wavelength and cutoff wavelength, then cause the extension or narrowing of cutoff band. Performance of thin film filter was composite result of two factors. Parameters of thin film filters can be amended according to the calculated value beforehand.

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